RAINFALL IMPACTS ON SUSPENDED SEDIMENT CONCENTRATIONS IN AN URBANIZED TIDAL CREEK, SOUTHEASTERN NORTH CAROLINA

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ABSTRACT

Elevated suspended sediment concentrations in fluvial systems are deleterious to fluvial ecosystems. In these systems, increases in total suspended solids (TSS) following rain events have been well documented. The impacts of rainfall on marsh surface sediments have received less attention. This study examined the relationship between rainfall and TSS in a tidal creek adjacent to upland and marsh surfaces.

TSS concentrations were measured for two locations in Bradley Creek in southeastern North Carolina; one tidal site and one non-tidal, headwater site. TSS concentrations at the tidal site were significantly higher during the growing season than during the non-growing season. The headwater site showed no significant change in TSS seasonally. No significant difference in TSS concentrations was found between spring and neap tides. During fair weather at the tidal site, flood tide TSS concentrations were greater than ebb tide TSS concentrations, which were greater than low tide TSS concentrations. Mean fair weather TSS concentrations at the headwater site were 1.0 mg L^{-1}. TSS concentrations increased to 11.9 mg L^{-1} following rain events. At the tidal site, mean fair weather TSS concentrations were 10.9 mg L^{-1} at ebb tide, 7.9 mg L^{-1} at low tide, and 13.5 mg L^{-1} at flood tide. At the tidal site, mean TSS concentrations following rain events increased to 22.5 mg L^{-1} at ebb tide, 21.8 mg L^{-1} at low tide, and 20.9 mg L^{-1} at flood tide.

These data suggest that following rain events in Bradley Creek, upland runoff has a greater impact on increasing TSS than does runoff from the marsh surface. It is not believed that a significant amount of sediment is removed from the marsh during low tide rain events.

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INTRODUCTION

Tidal creek watersheds are a major landscape feature of the Atlantic Coastal Plain in the southeastern United States. They provide an ecosystem for many flora and fauna and their potential to buffer storm surges provides flood protection from hurricanes and nor'easters (Mitsch and Gosselink 1993). Tidal creeks are the first order connection between the upland and marsh environments, and upland construction has led to high levels of pollutants in the downstream reaches of many of these systems (Holland et al. 2004). Total suspended solid (TSS) loading is of great importance because increased TSS causes light limitation for aquatic flora (Hopkinson and Vallino 1995), impacts shellfishing (Mallin et al. 2000), and enhances pollutant transport in the system (Warren and Zimmerman 1993; Mallin et al. 2001). Siltation has led to the overall degradation of tidal creek environments, including the closure of some tidal creeks to shellfishing (Mallin et al. 2000; Holland et al. 2004).

An extensive body of salt marsh literature exists that has focused on water quality (Mallin et al. 2000; Holland et al. 2004), sediment transport (Ward 1981; Leonard 1997; Christiansen et al. 2000; Friedrichs and Perry 2001), sediment deposition (Leonard 1996; Leonard 1997; Friedrichs and Perry 2001), and tidal flow (Bayliss-Smith et al. 1979; Leonard and Luther 1995; Christiansen et al. 2000; Friedrichs and Perry 2001) in tidal creeks. TSS concentrations are controlled largely by the tides; specifically tidal velocity, hydroperiod, and tidal stage (Mitch and Gosselink 1993; Leonard et al. 1995; Christiansen et al. 2000; Friedrichs and Perry 2001). The sediment source concentration and distance from the source are also influential and determine how much sediment is available to the system (Friedrichs and Perry 2001). Several biological controls exist as well. Vegetation slows flow velocities and promotes sediment trapping (Leonard 1996; Friedrichs and Perry 2001) on adjacent marsh surfaces and root systems act as sediment stabilizers in addition to providing below-ground biomass (Mitch and Gosselink 1993). Bioturbation by fiddler crabs or other organisms reworks surface sediments thereby enhancing potential for transport by tidal flows (Mitch and Gosselink 1993; Leonard et al. 1995; Friedrichs and Perry 2001). Fiddler crabs and other macrofauna also contribute to the sediment budget of these systems through deposition of fecal material on the marsh surface (Leonard et al. 1995). The single factor, however, most widely recognized to cause major changes in the sediment budget of tidal creek systems is storms. Storms that coincide with strong winds, increased tidal prisms, and increased current velocities cause a higher rate of sediment re-suspension and transport (Ward 1981; Leonard et al. 1995). In addition, raindrop impacts break up exposed channel bank and surface sediments making them more vulnerable to transport within the system (Settlemyre and Gardner 1975; Ward 1981; Mwamba and Torres 2002). On the other hand, increased surface water levels protect the marsh and reduce the effects of raindrop impacts (Moss and Green 1983; Voulgaris and Meyers 2004)

The impacts of rainfall on marsh surface sediment redistribution have received less attention than other factors and little scientific literature concentrates on this issue directly. Most of the literature available regarding rain-induced erosion focuses on upland agricultural applications, but the fundamental theories can be applied to salt marsh surfaces. By understanding these theories and the flow patterns on salt marshes, one can predict the impact a rain event might have on marsh sediment redistribution.

Three major processes influence the transport of sediment in a marsh environment: (1) re-suspension and dispersion, (2) sheet flow, and (3) tidal flow (Mwamba and Torres 2003). Re-suspension and dispersion can occur via biological processes (Ward 1981), surface water flow (Walker et al. 1978; Nepf et al. 1997; Nelson and Booth 2002), and raindrop impacts (Walker et al. 1978; Green and Houk 1980; Ward 1981; Hartley and Alonso 1991; Mwamba and Torres 2003; Voulgaris and Meyers 2004). The amount of sediment re-suspended by raindrop impact is influenced mostly by water layer depth, drop size and velocity, and viscosity (Hartley and Alonso 1991). Generally, rainsplash will re-suspend less sediment when a deep surface water layer is present as compared to a shallow or nonexistent surface water layer. Consequently, a shallow layer of water will provide less of a cushion for the surface thus exposing sediments to increased potential erosion (Green and Houk 1980; Hartley and Alonso 1991; Mwamba and Torres 2003; Voulgaris and Meyers 2004). This factor is very important, especially when considering tidal salt marshes, due to prolonged periods when the marsh surface is emergent or covered by water depths of a few centimeters. Drop size and velocity are also important because larger, faster moving raindrops will cause greater rainsplash than smaller, slower moving raindrops (Green and Houk 1980). However, these factors may be of less consequence in marshes because the vegetation canopy intercepts the drops prior to impact.

During a rain event, water that has not infiltrated the soil turns into sheet flow. Sediment re-suspended by rainsplash may land in a preexisting sheet flow, entraining the eroded sediment and moving it further away from its original location (Mwamba and Torres 2003). Although sheet flow alone also has the potential to re-suspend sediments, the amount re-suspended is usually low due to low flow velocities (Leonard and Luther 1995). Rainsplash and sheet flow together force sediments to move more easily than they do as separate processes (Walker et al. 1978). However, the formation of sheet flow on the surface would increase the surface water layer depth thereby decreasing the effect of raindrop impacts on sediment redistribution (Hartley and Alonso 1991).

The final process influencing sediment transport in a marsh environment is tidal flow. This process is important because it has the potential to carry sediments over long distances. Leonard (1997) found that in Bradley Creek, NC flood tide waters follow topographic lows as they move onto the marsh and turn into sheet flow as water levels increase. The process is reversed during the ebb tide. Therefore, it seems likely that sediments re-suspended during a low tide rain event would be transported landward during the next rising tide and fall out of suspension during high tide. Tidal flows could also amplify sediment removal from the channel banks (Frey and Basan 1985).

Studies conducted in a pristine tidal salt marsh environment have shown increased TSS concentrations within the creek following low tide rain events. Voulgaris and Meyers (2004) determined that TSS concentrations were almost 2.5 times greater as compared to times without any rain. Rain events occurring during high tide when water protected the marsh surface, had little impact on TSS concentrations within the tidal creek. Mwamba and Torres (2002) determined that during rainfall events, TSS concentrations were 2 to 100 times larger than those under artificial inundation of the surface. This result suggests that little sediment is re-suspended by sheet and tidal flows alone and is consistent with other studies (Leonard et al. 1995; Leonard and Luther 1995; Christiansen et al. 2001) that suggest that low shear stresses produced during overmarsh flows are insignificant to resuspend sediments from the marsh surface.

While understanding flow and resuspension on a marsh surface is important, it is also essential to understand the influence of rainfall in the urbanized headwater reaches present in some tidal creek environments. Typically, the volume and velocity of runoff is higher in urbanized areas due to the large proportion of impervious surfaces (Hollis 1975; Schueler 1994; Hopkinson and Vallino 1995; Arnold and Gibbons 1996; Nelson and Booth 2002; Old et al.

2003; Viessman and Lewis 2003; Holland et al. 2004). This amplification of runoff causes increased channel erosion (Schueler 1994; Hopkinson and Vallino 1995; Arnold and Gibbons 1996; Nelson and Booth 2002; Viessman and Lewis 2003). Another characteristic of an urbanized watershed is a shorter lag time between peak rainfall and peak runoff. Watersheds with a high volume of impervious surfaces tend to experience peak runoff more quickly than watersheds of pristine nature due to increased surface runoff velocity and decreased groundwater recharge (Hollis 1975; Hopkinson and Vallino 1995; Old et al. 2003; Viessman and Lewis 2003).

The purpose of this project was to examine the effect of rainfall on suspended sediment concentrations in Bradley Creek, North Carolina. The main objectives were to:

- determine if TSS concentrations in the creek following rainfall events are greater than concentrations during dry periods;
- determine the effect of upland runoff on TSS concentrations in the downstream tidal reaches;
- determine if a seasonal fluctuation in TSS exists within the system due to changes in precipitation and stem density of marsh vegetation;
- determine if significant differences in TSS concentrations exist between spring vs. neap tide rain events; and
- determine if differences in TSS concentrations associated with rainfall events are dependent on the presence or absence of water on the marsh surface (i.e. high or low tide).

It was hypothesized that 1) TSS concentrations in the tidal creek following rain events are greater than during dry periods, 2) TSS concentrations in the headwater drainages of the urbanized uplands exhibit greater relative increases following rain events than TSS concentrations at the tidal site 3) summer TSS concentrations exceed winter TSS concentrations, 4) spring tides produce higher TSS concentrations in the tidal reach of the creek than neap tides, and 5) TSS concentrations in the tidal creek following a low tide rain event are greater than TSS following rain events during other tidal stages.

STUDY LOCATION

This study was conducted in the Bradley Creek watershed, New Hanover County, North Carolina. This creek drains into the Atlantic Intracoastal Waterway (ICWW) between the mainland and barrier islands of New Hanover County. Bradley Creek is an urbanized watershed that lies completely within New Hanover County and has an area of about 24 km^2. Only 20 percent of the watershed is undeveloped. The other 80 percent includes land cover types of roads, parking lots, and buildings. Land use within the watershed includes single family residential (32 percent), recreational (about 6 percent), transportation (11 percent), and commercial areas (about 5 percent) (Mallin et al. 2000; Halls 2002).

Two locations along the creek were examined: one non-tidal headwater site (H) and one tidally influenced site (T). The headwater site is dominated by fresh water and is located at N 34° 13.846' latitude, W 77° 51.141' longitude. The tidal site is dominated by brackish water and is located at N 34° 13.186' latitude, W 77° 50.747' longitude (Figure 1). The tidal reaches of the creek are immediately surrounded by salt marshes composed primarily of *Spartina alterniflora* in the low marsh with *Juncus roemerianus* established further from the channel in the high marsh (Figure 2a). Bradley Creek experiences a semi-diurnal tide with a diurnal inequality and a mean tidal range of about 1.1 m. About 3 km^2 of the lower watershed is intertidal marsh. The non-tidal, headwater reaches of the creek are forested and highly urbanized with culverts throughout (Figure 2b). Water depth at this site is less than 0.3 m on average.

Soils at the tidal site are very poorly drained with a high concentration of organic material. Sandy channels dominate the creek with finer materials being deposited on the tidal floodplain (i.e. marsh). The soil adjacent to this site, at a higher elevation, is better drained with a coarser texture (Craven series). Soils at the headwater site are also very poorly drained and are

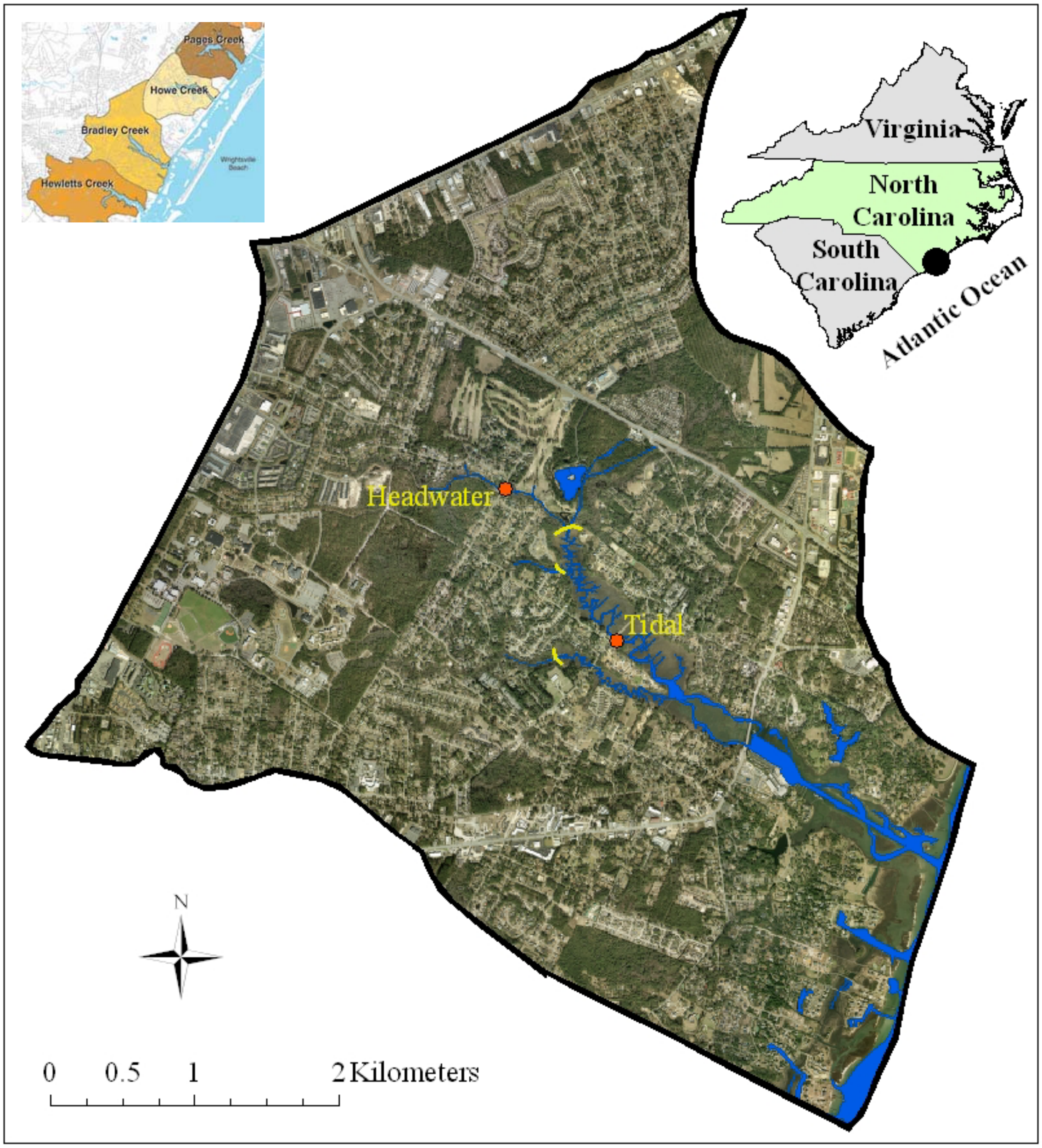


Figure 1. Map and aerial photograph of study area showing locations of both sampling sites. The aerial photos (New Hanover County GIS department 2002) used here show the extensive urbanization of the Bradley Creek watershed. The yellow lines across portions of the creek represent the head of tides.

Figure 2. Photographs of a) tidal site looking downstream and b) headwater site looking upstream into a culvert. These photographs were taken on August 2, 2004 and July 28, 2004, respectively.

predominantly quartz sand (Murville series). This series typically occurs in upland depressions such as small creeks. On the floodplain adjacent to the creek are well-drained, sandy soils usually located on ridges (Weaver 1977).

The study location lies in a humid subtropical climate. Precipitation is caused mostly by mid-latitude wave cyclones during the winter and convective storms in the summer. Tropical systems are also important between June and October (USGS 1991). The majority of precipitation occurs during the summer months of July through September. Average annual rainfall is about 148 cm. Average summer temperatures range from 29°C to 32°C and winter temperatures range from 13°C to 19°C. Vegetative growth peaks during the summer due to increased temperatures and precipitation. During the winter, decreased temperatures, reduced evapotranspiration, decreased vegetative cover, and reduced infiltration causes discharge rates to be at their highest. November exhibited the least vegetative cover and lowest protection to the marsh, whereas April exhibited the most vegetative cover and greatest protection to the marsh (Table 1).

MATERIALS AND METHODS

Three one-L replicate water samples were collected once per week, for one year (June 2004 – July 2005), at low (L), peak flood (F), and peak ebb (E) tide. Additional samples were collected during or after rain events. The time frame for rain-event sample collection varied depending on tidal stage. Water was collected using a Niskin bottle, then was poured into one-L Nalgene bottles, transported to the laboratory, and refrigerated after all samples had been collected. At the tidal site, about 50 percent of the flood tide samples were collected when the marsh surface was inundated with water. Samples were then analyzed for TSS concentration, percent organic content, and percent inorganic content. To determine TSS, water samples were

Date	Stems m^{-2}
11/22/2004	99
12/14/2004	108
1/10/2005	108
2/21/2005	126
3/21/2005	285
4/25/2005	351
6/8/2005	171
6/29/2005	198

Table 1. Plant densities measured during the study period.

vacuum filtered through pre-combusted, pre-weighed 47 mm glass fiber filters. The filters were oven-dried at 60 °C for at least 24 hours, re-massed and concentration given in mg L^{-1}. To determine percent organic content of TSS, filters were combusted in a muffle furnace for four hours at 450 °C and re-massed.

Continuous rainfall data were collected using a Davis tipping bucket connected to a Hobo Event Rainfall Logger located on a dock at the tidal site. For every 0.2 mm of rain, one tipping event was recorded on the data logger and the collected data were downloaded no less than once per month. From these data, hourly and daily rainfall amounts were calculated in addition to storm durations and intensities.

Marsh surface water level data also were collected using a Remote Data Systems WL Series piezometer deployed at the tidal site. The piezometer was installed near the center of the *Spartina alterniflora* marsh where recorded water levels would be representative of the entire marsh. Water level readings were recorded every 24 minutes and data were downloaded on a weekly basis. These data provide information on the duration of marsh inundation and the depth of water on the marsh surface throughout inundation events. In addition, channel water depths were measured at both sites when TSS samples were collected to delineate tidal stage and relative changes in flow volume during sampling.

Runoff from the marsh surface, collected during low tide rain events, was measured using metal cylinders placed into the marsh that were surrounded by 5 cm high round strips of a 5-gal plastic bucket (Figure 3). The strips were 23-25 cm in diameter (area=0.06 m^2) and were pushed into the marsh so that about 2.5 cm remained above the surface. Plastic cups were placed inside the metal cylinders, flush with the marsh surface, when a low tide rain event was expected. During the rain event, material moved along the marsh surface within the enclosed

Figure 3. Photograph of runoff collection device at tidal site. Photograph taken on September 15, 2004.

area and was deposited in the cups. The cups were removed before the marsh was flooded by the next tidal inundation event. Material deposited in the cups was rinsed out with deionized water and vacuum filtered through pre-weighed 9 cm glass fiber filters. The filters were then oven-dried at 60 °C for at least 24 hours and remassed.

Finally, salt marsh canopy stem densities were measured. Densities were measured using a 33 cm^2 PVC pipe quadrate and specific measuring points were blindly selected. Three replications were measured once per month for the majority of the sampling period. The purpose of this was to examine the role of seasonal changes in biomass, as measured by stem density, on raindrop impacts and marsh sediment movement.

Analytical analyses for TSS and ISS consisted of descriptive statistics, analysis of variance (ANOVA) and correlation analysis (Spearman, non-parametric). The ANOVA was conducted to determine significant differences between TSS concentrations measured during ebb, low, and flood tides; fair weather versus rain events; seasonal variations; spring and neap variations; and high tide versus low tide rain events. Descriptive statistics were used to obtain the mean value and standard error of data. To determine relationships between TSS and precipitation, correlation analyses were conducted. All statistical analyses were performed with STATISTICA 5.1 software using a significance level of 0.05.

RESULTS

Precipitation

Precipitation in the study area was greatest during the growing season (March - September). Annual precipitation was 1579.8 mm between July 2004 and June 2005 and monthly precipitation ranged from 28.8 mm in February 2005 to 274.8 mm in August 2004.

Values for all months during the sampling period are shown in Figure 4. The growing season produced more precipitation than the non-growing season (October - February) with 1,353.7 mm and 226.1 mm, respectively.

Four tropical systems impacted the study area in 2004. Rainfall from Hurricane Alex totaled 40.4 mm between July 31, 2004 and August 4, 2004. Hurricane Charley hit the study area on August 14, 2004, however rain associated with this event fell for over 48 hours producing 171.2 mm between August 13 and August 16. On August 30, 2004 Hurricane Gaston impacted the study area but produced little rain (11.6 mm). Finally, Hurricane Jeanne (September 28, 2004) had a small impact producing 9.2 mm of rain. These systems produced an above average growing season precipitation total.

During the study period, there were 100 days with at least 1 mm of rain of which 19 events were sampled for TSS. Rainfall totals for the sampled days ranged from 1.4 mm to 72.4 mm with intensities ranging from 0.2 mm hr^{-1} to 11.5 mm hr^{-1} (Table 2). Precipitation totals were calculated by summing the total amount of precipitation in the 12 hours preceding the collection of each TSS sample. Intensities were calculated by dividing the total 12 hour precipitation totals by the duration of the event in hours. Extreme rain events were defined as those with at least 20.2 mm of rain or an intensity of at least 3.9 mm hr^{-1} (greater than one standard deviation above the mean). Of the 19 rain events sampled, six of them qualified as extreme rain events, only one of which occurred only during low tide when the marsh surface was not inundated.

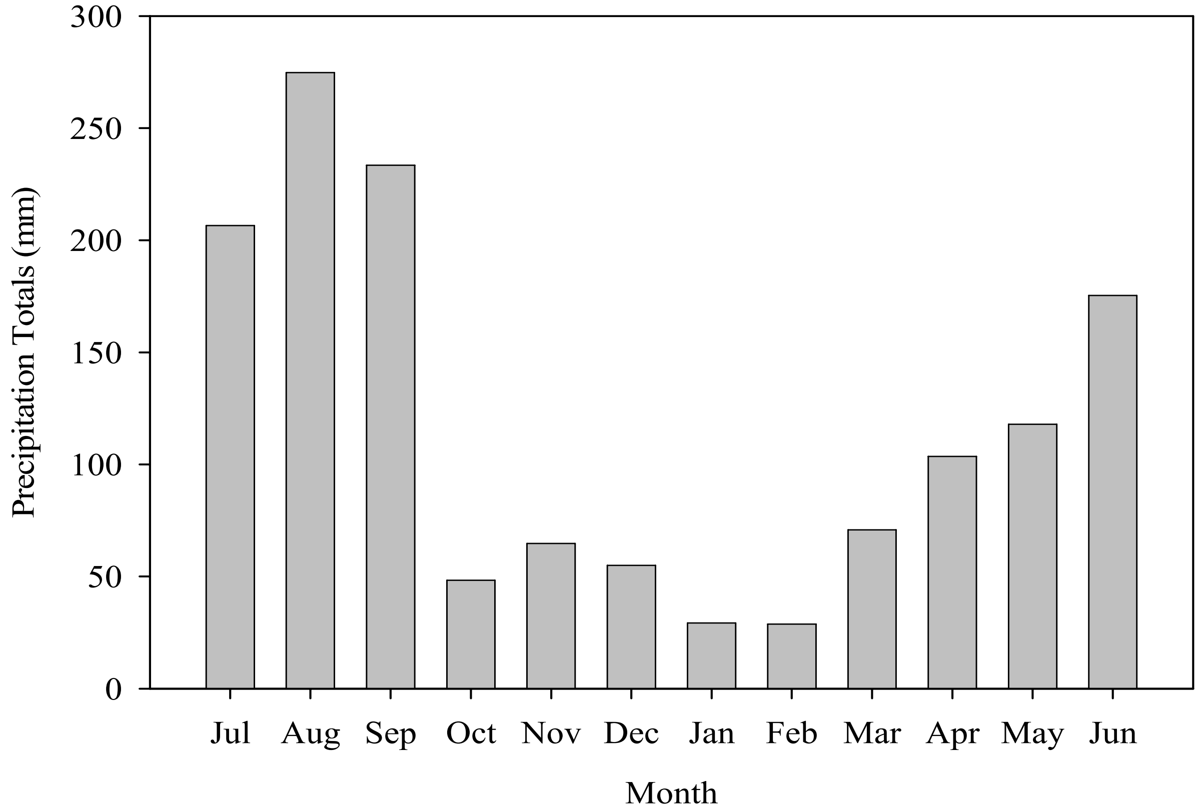


Figure 4. Monthly precipitation during the study period. The growing season maximum is generally not this pronounced and was caused by numerous tropical systems that passed through the study are in August 2004.

	Ebb		Low		Flood	
Date	Precipitation	Intensity	Precipitation	Intensity	Precipitation	Intensity
6/28/04	6.4	3.2	6.4	3.2	N/A	N/A
7/12/04	N/A	N/A	N/A	N/A	**22.9**	**11.5**
7/28/04	9.0	1.8	9.4	1.1	9.4	2.3
8/2/05	N/A	N/A	3.8	0.4	4.8	0.7
8/16/04	2.2	0.2	2.2	0.2	2.2	0.2
9/15/04	N/A	N/A	5.8	2.9	N/A	N/A
9/27/04	7.9	**3.9**	N/A	N/A	N/A	N/A
10/15/04	15.0	2.5	15.0	2.5	N/A	N/A
1/14/05	18.5	3.1	N/A	N/A	4.8	**4.8**
2/24/05	1.9	0.3	3.4	0.3	4.6	0.4
2/28/05	6.6	0.5	7.5	0.6	3.3	0.3
3/17/05	N/A	N/A	1.4	0.3	N/A	N/A
3/23/05	2.2	0.2	7.0	1.2	7.0	1.2
3/28/05	19.0	**9.5**	19.2	1.9	10.0	1.0
4/1/05	1.5	0.8	N/A	N/A	N/A	N/A
5/5/05	N/A	N/A	N/A	N/A	5.3	1.8
5/24/05	N/A	N/A	N/A	N/A	2.0	0.4
6/2/05	13.2	1.1	18.6	1.5	**24.2**	2.0
6/29/05	**24.4**	2.4	**30.7**	3.4	**72.4**	**6.0**

Table 2. Precipitation totals and intensities for rain events during the sampling period. Precipitation (mm) is the sum of all precipitation during the 12 hours before sample collection. Intensity (mm hr^{-1}) is the sum of precipitation divided by the event duration. N/A represents samples that did not qualify as rain events. Extreme rain events are bolded.

Water Level

Channel water depths varied at the tidal site based on tidal type (i.e. spring or neap) and tidal stage (i.e. ebb, low, or flood). Other factors including wind, rain, and storm surge were not evident during this study. At the headwater site, water depths were influenced mainly by precipitation. Channel water depths at the tidal site ranged from 1.14 m (low) to 2.34 m (flood). No significant difference in tidal range was detected between spring and neap tides. Mean water levels were 1.59 m, 1.40 m, and 2.06 m for ebb, low, and flood tide, respectively. At the headwater site, where no tidal influence is present, water depths ranged from 0.10 m to 0.48 m and were significantly greater ($p<0.0001$) following rain events.

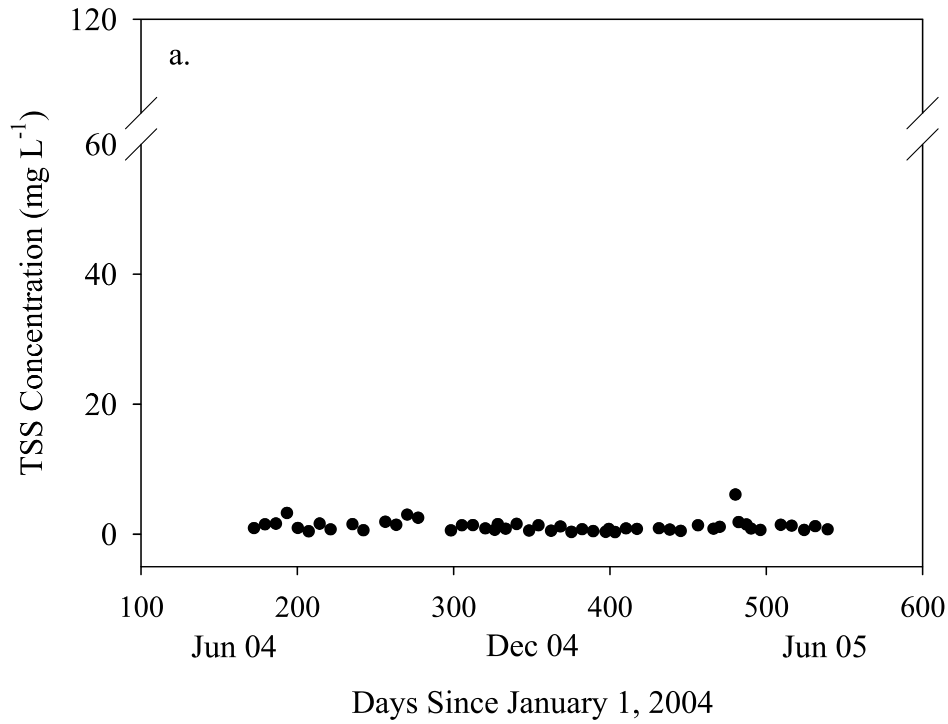
Water levels on the marsh surface varied depending on tidal type. Higher water levels were measured on the marsh during spring tides than during neap tides, however these differences were not significant ($p>0.05$). Other potential influences on water levels are wind and storm surge; however, the limited reliability of the piezometer made it difficult to determine if these influences were a factor in this study. In addition, water levels during the first four months of the study period were not measured because the piezometer had not yet been installed. Therefore, increased water levels from storm surges associated with hurricanes were not measured. Of the readings that were available, the highest water level recorded on the marsh surface was 0.60 m, which occurred during a spring tide. The mean hydroperiod was about 3.5 hours during a mid-tide. Spring tides and neap tides exhibited longer and shorter hydroperiods, respectively.

Fair Weather

Total Suspended Solids

TSS concentrations at the tidal site were higher than TSS concentrations at the headwater site during fair weather. At the tidal site, low tide TSS concentrations were lower than both ebb tide and flood tide TSS concentrations. Mean TSS concentrations ranged from 0.1 ± 0.0 [standard error = standard deviation (σ) / n] mg L^{-1} to 5.9 ± 0.0 mg L^{-1} at the headwater site with a mean of 1.0 ± 0.0 mg L^{-1} (Figure 5). At the tidal site, mean TSS concentrations generally ranged from 3.0 ± 0.2 mg L^{-1} to 20.2 ± 0.2 mg L^{-1} with one exceptional concentration of 60.9 ± 0.2 mg L^{-1} (Figure 5). The mean fair weather TSS concentration at the tidal site was 10.8 mg L^{-1}. Ebb tide concentrations at the tidal site ranged from 2.2 ± 0.1 mg L^{-1} to 26.5 ± 0.1 mg L^{-1} with a mean of 10.9 mg L^{-1}. Low tide concentrations at this site ranged from 1.1 ± 0.1 mg L^{-1} to 23.0 ± 0.1 mg L^{-1} with a mean of 7.9 mg L^{-1}, and flood tide values ranged from 4.4 ± 0.2 mg L^{-1} to 60.9 ± 0.2 mg L^{-1} with a mean of 13.5 mg L^{-1}. At the tidal site, ebb tide and flood tide TSS concentrations were significantly higher than TSS concentrations during low tide ($p=0.0092$ and $p=0.0007$, respectively). TSS concentrations also were significantly higher at the tidal site than at the headwater site for all tidal stages ($p<0.0001$).

Seasonal differences in TSS concentrations existed at the tidal site. In general, TSS concentrations at the tidal site were lowest in December, January, and February. TSS concentrations were least variable in March while the most variability occurred in June. TSS concentrations were significantly higher during the growing season, which lasts from March through September, than during the non-growing season, which lasts from October through February ($p=0.0004$). At the tidal site, the mean TSS concentration during the growing season was 14.9 ± 0.3 mg L^{-1}, which was higher than the non-growing season concentration of 6.7 ± 0.1



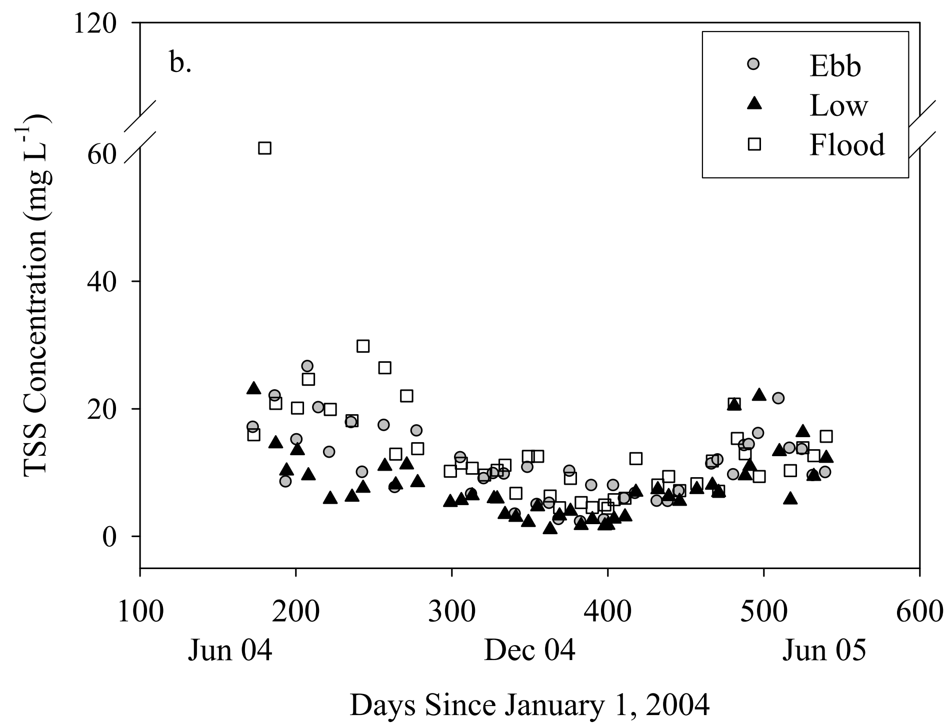


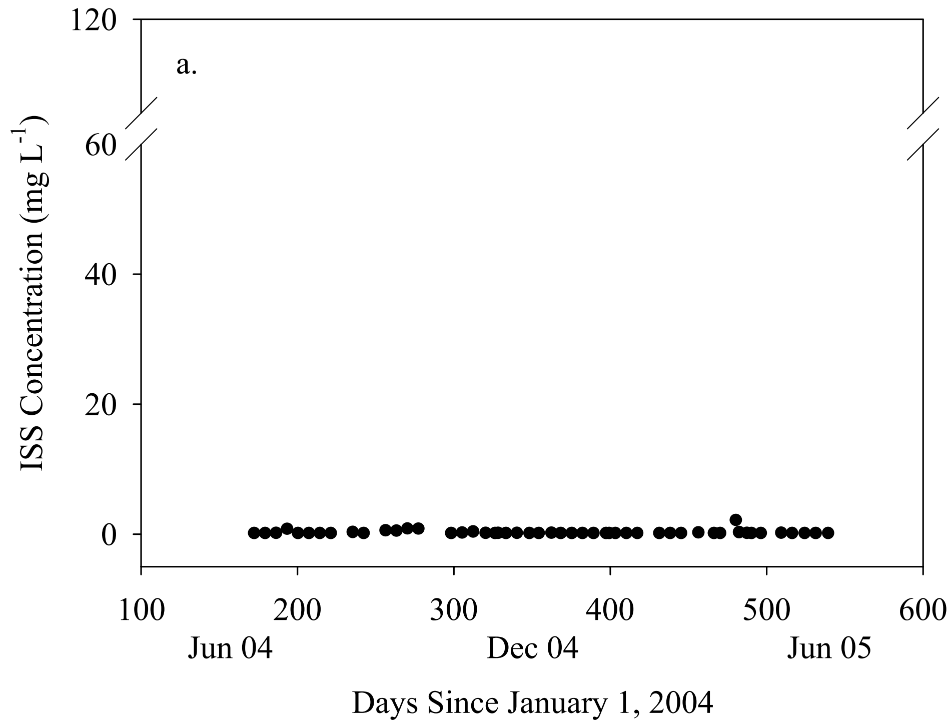
Figure 5. TSS concentrations at the (a) headwater site and (b) tidal site under fair weather conditions.

mg L^{-1}. At the headwater site, no seasonal variations existed and TSS concentrations were near 1.0 mg L^{-1} throughout the year (Figure 5). Mean fair weather TSS concentrations at the headwater site were 1.3 ± 0.0 mg L^{-1} during the growing season and 0.8 ± 0.0 mg L^{-1} during the non-growing season.

Mean spring tide TSS concentrations during fair weather conditions were higher than neap tide concentrations at the tidal site. Mean spring tide TSS concentrations ranged from 5.0 ± 0.9 mg L^{-1} to 18.2 ± 0.9 mg L^{-1} with means of 12.0 ± 0.8 mg L^{-1} at ebb tide, 8.8 ± 0.9 mg L^{-1} at low tide, and 16.1 ± 1.8 mg L^{-1} at flood tide. Neap tide concentrations ranged from 3.0 ± 0.3 mg L^{-1} to 14.0 ± 0.3 mg L^{-1} with means of 8.6 ± 0.5 mg L^{-1} at ebb tide, 5.3 ± 0.2 mg L^{-1} at low tide, and 9.0 ± 0.4 mg L^{-1} at flood tide. While spring tides produced higher TSS concentrations, they were not significantly higher than neap tide concentrations.

Inorganic Suspended Solids

During fair weather, ISS concentrations at the headwater site were lower than ISS concentrations at the tidal site (Figure 6). Also, low tide ISS concentrations at the tidal site were lower than ebb tide or flood tide concentrations. Fair weather ISS made up ten percent and 56 percent of TSS at the headwater and tidal sites, respectively. ISS concentrations ranged from values below the detectable resolution to 2.0 mg L^{-1} at the headwater site with a mean of 0.1 mg L^{-1} (Figure 6). At the tidal site, ISS concentrations ranged from 0.7 ± 0.1 mg L^{-1} to 18.5 ± 0.1 mg L^{-1} with one exceptional concentration of 51.6 ± 0.1 mg L^{-1} (Figure 6). The mean fair weather ISS concentration at the tidal site was 6.1 mg L^{-1}. Ebb tide concentrations at the tidal site ranged from values below the detectable resolution to 19.3 ± 0.1 mg L^{-1} with a mean of 6.3 mg L^{-1}. Low tide concentrations at this site ranged from values below the detectable resolution



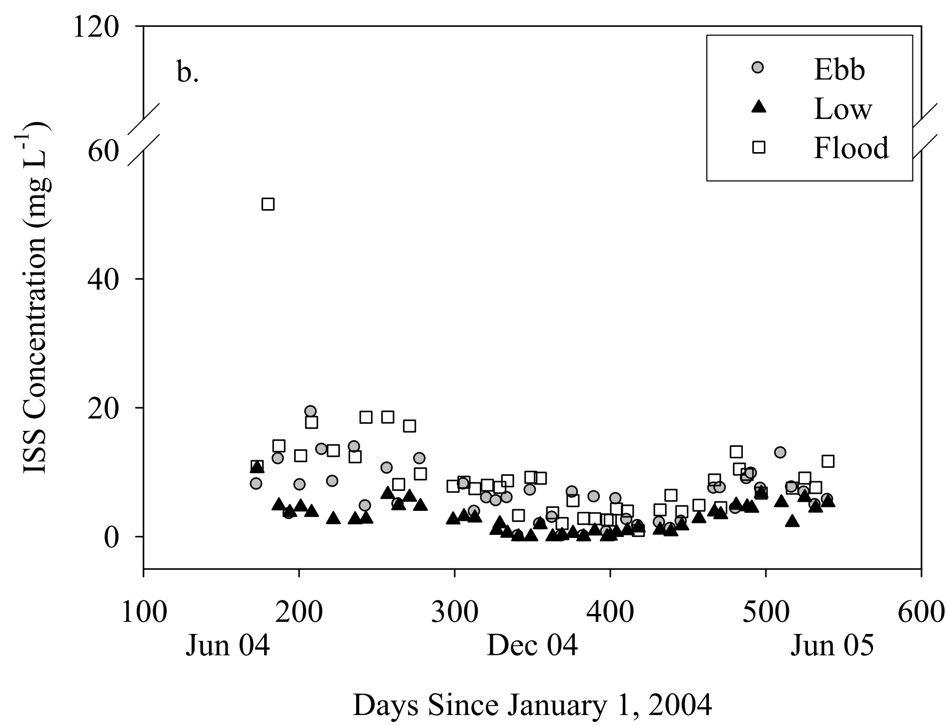


Figure 6. ISS concentrations at the (a) headwater site and (b) tidal site under fair weather conditions.

to 10.6 ± 0.1 mg L^{-1} with a mean of 2.9 mg L^{-1}. Flood tide values ranged from 1.0 ± 0.2 mg L^{-1} to 51.6 ± 0.2 mg L^{-1} with a mean of 9.2 mg L^{-1}. At the tidal site, ebb tide and flood tide ISS concentrations were significantly higher than ISS concentrations during low tide ($p<0.0001$). Flood tide ISS concentrations also were significantly higher than ebb tide concentrations ($p=0.0358$). In addition, ISS concentrations at the tidal site also were significantly higher at the tidal than at the headwater site for all tidal stages ($p<0.0001$) during fair weather.

Seasonal differences in ISS concentrations were apparent at the tidal site during fair weather conditions (Figure 6). During the growing season, which lasts from March through September, ISS concentrations at the tidal site were significantly higher than during the non-growing season, which lasts from October through February ($p=0.0074$). At the tidal site, the mean ISS concentration during the growing season was 8.8 ± 0.3 mg L^{-1} (59 percent of TSS), which was higher than the non-growing season concentration of 3.7 ± 0.1 mg L^{-1} (55 percent of TSS). Significant seasonal variations in ISS concentration did not exist at the headwater site. Mean fair weather ISS concentrations at the headwater site were consistently near 0.2 mg L^{-1} (15 percent of TSS) during the growing season and 0.1 mg L^{-1} (12 percent of TSS) during the non-growing season.

At the tidal site, mean spring tide ISS concentrations ranged from 3.2 ± 0.5 mg L^{-1} to 11.9 ± 0.5 mg L^{-1} with means of 7.3 ± 0.5 mg L^{-1} (61 percent of TSS) at ebb tide, 3.1 ± 0.4 mg L^{-1} (35 percent of TSS) at low tide, and 10.5 ± 1.2 mg L^{-1} (60 percent of TSS) at flood tide. Neap tide concentrations ranged from 0.7 ± 0.2 mg L^{-1} to 9.6 ± 0.2 mg L^{-1} with means of 5.0 ± 0.4 mg L^{-1} (58 percent of TSS) at ebb tide, 2.2 ± 0.2 mg L^{-1} (42 percent of TSS) at low tide, and 5.8 ± 0.3 mg L^{-1} (64 percent of TSS) at flood tide. These data suggest that settling of inorganic material is occurring prior to low tide. While spring tides produced higher ISS concentrations, they were not significantly higher than neap tide ISS concentrations.

Rain Events

Total Suspended Solids

TSS concentrations during rain events were generally higher and more variable than fair weather TSS concentrations at both sites. Mean TSS concentrations during rain events ranged from 0.7 ± 0.7 mg L^{-1} to 54.5 ± 0.7 mg L^{-1} at the headwater site with a mean of 11.9 ± 0.7 mg L^{-1}, which is about 12 times higher than the fair weather mean TSS concentration (Figure 7). At the tidal site, TSS concentrations ranged from 5.8 ± 0.7 mg L^{-1} to 52.8 ± 0.7 mg L^{-1} with a mean of 21.7 mg L^{-1}, which is about two times higher than the fair weather mean TSS concentration (Figure 7). Ebb tide concentrations at the tidal site ranged from 7.8 ± 1.5 mg L^{-1} to 77.3 ± 1.5 mg L^{-1} with a mean of 22.5 ± 1.5 mg L^{-1}. Low tide concentrations at this site ranged from 5.8 ± 1.4 mg L^{-1} to 65.2 ± 1.4 mg L^{-1} with a mean of 21.8 ± 1.4 mg L^{-1}. Flood tide values ranged from 7.9 ± 1.1 mg L^{-1} to 57.6 ± 1.1 mg L^{-1} with a mean of 20.9 ± 1.1 mg L^{-1}. A significant difference existed between mean TSS concentrations at the tidal site and mean TSS concentrations at the headwater site ($p=0.0115$). No significant difference in TSS concentrations existed between tidal stages during rain events. TSS concentrations following rain events were significantly higher ($p<0.05$) than TSS concentrations measured during fair weather conditions at both sites for all tidal stages (Table 3, Appendix A). However, TSS concentrations following extreme rain events were not significantly higher than concentrations measured during non-extreme rain events.

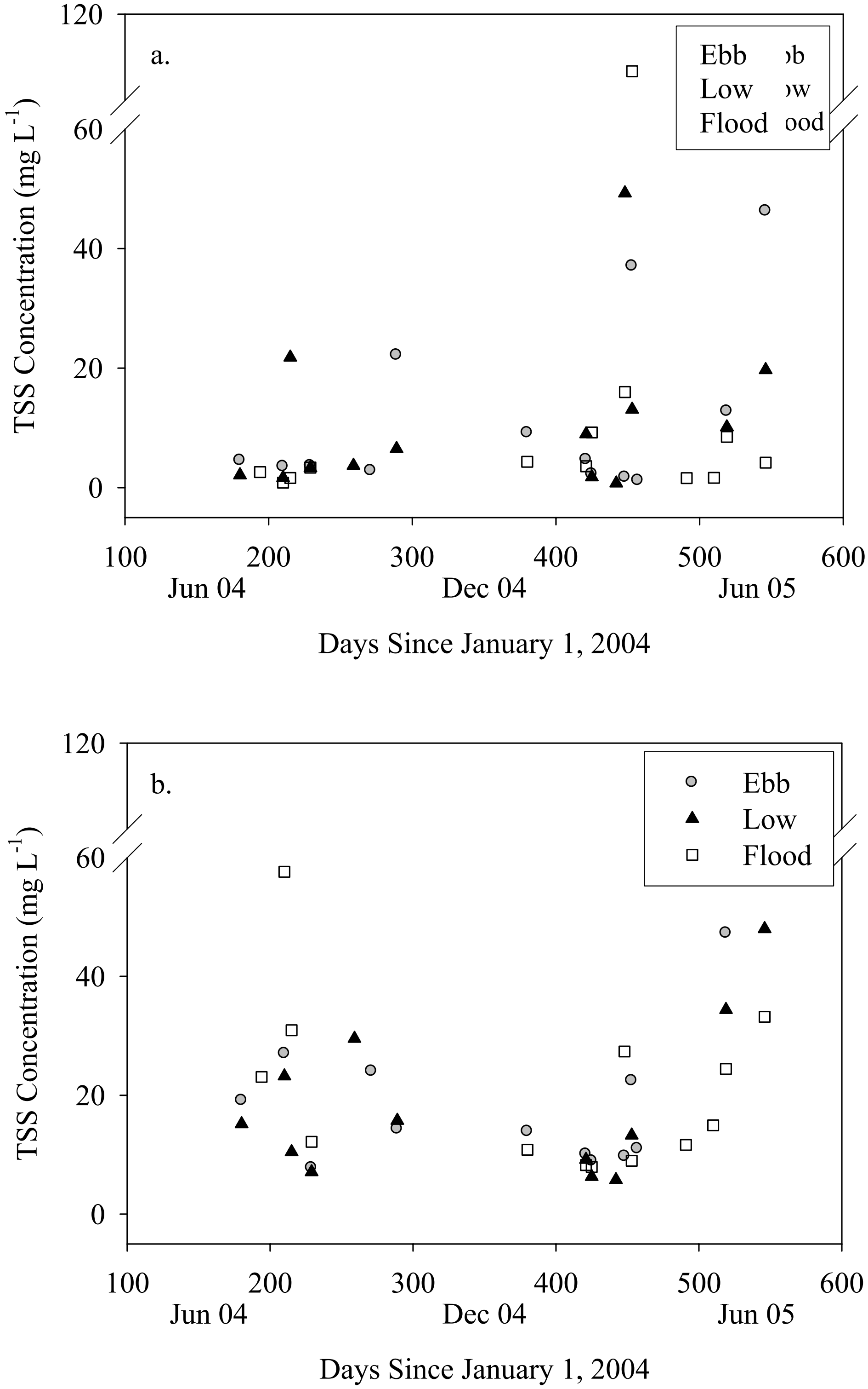


Figure 7. TSS concentrations at the (a) headwater site and (b) tidal site following rain events. Headwater values are broken down by tidal stage simply for comparison with the tidal site.

	TSS		ISS	
	Tidal	Headwater	Tidal	Headwater
Ebb	0.0010 R>F	<0.0001 R>F	0.0014 R>F	<0.0001 R>F
Low	<0.0001 R>F	<0.0001 R>F	<0.0001 R>F	<0.0001 R>F
Flood	0.0318 R>F	0.0086 R>F	0.0998 R≤F	0.0127 R>F

Table 3. P-values for ANOVA of TSS and ISS concentrations during fair weather versus rain events. Columns next to p-values show the relationship between mean rain values (R) and mean fair weather values (F).

Post-rain TSS concentrations were not significantly different between seasons at either site and TSS concentrations were more variable overall. TSS concentrations at the tidal site were 26.8 ± 0.9 mg L^{-1} during the growing season and 15.0 ± 0.8 mg L^{-1} during the non-growing season. Growing season TSS concentrations were less than two times greater than during fair weather and non-growing season TSS concentrations were more than two times greater following rain events than during fair weather. At the headwater site, the mean TSS concentrations were 13.5 ± 1.0 mg L^{-1} and 7.0 ± 1.1 mg L^{-1} for the growing season and non-growing season, respectively. Following rain events, TSS concentrations at the headwater site exhibited a 10-fold and nine-fold increase during the growing season and non-growing season, respectively. TSS concentrations at the tidal and headwater sites were significantly higher ($p<0.05$) following rain events than concentrations measured under fair weather conditions for both the growing season and non-growing season (Table 4, Appendix B).

Overall, neap tide concentrations were higher following rain events than during fair weather. In addition, post-rain neap tide concentrations were higher than post-rain spring tide concentrations. Mean spring tide concentrations following rain events ranged from 9.0 ± 1.8 mg L^{-1} to 29.5 ± 1.8 mg L^{-1} with means of 14.0 ± 2.9 mg L^{-1} at ebb tide, 15.3 ± 4.1 mg L^{-1} at low tide, and 11.8 ± 1.1 mg L^{-1} at flood tide. Of the sampled rain events, only one occurred during neap tide. For that event, neap tide concentrations ranged from 33.2 mg L^{-1} to 77.3 mg L^{-1} with values of 77.3 mg L^{-1} at ebb tide, 48.0 mg L^{-1} at low tide, and 33.2 mg L^{-1} at flood tide. No statistical analyses were conducted between post-rain spring tide and neap tide rain events due to the low occurrence of sampled neap tide rain events during the study period. No significant differences existed between post-rain spring tide concentrations and fair weather concentrations (Table 5, Appendix C).

	TSS				ISS			
	Tidal		Headwater		Tidal		Headwater	
Growing	0.0332	R>F	0.0028	R>F	0.0610	R≤F	0.0045	R>F
Non-Growing	0.0072	R>F	<0.0001	R>F	0.0885	R≤F	<0.0001	R>F

Table 4. P-values for ANOVA of TSS and ISS concentrations during fair weather versus rain events during the growing season and non-growing season. Columns next to p-values show the relationship between mean rain values (R) and mean fair weather values (F).

	TSS		ISS	
Ebb	0.6663	R≤F	0.5548	R≤F
Low	0.2983	R≤F	0.1633	R≤F
Flood	0.5452	R≤F	0.4416	R≤F

Table 5. P-values for ANOVA of TSS and ISS concentrations during fair weather versus rain events for each tidal stage during spring tides. Columns next to p-values show the relationship between mean rain values (R) and mean fair weather values (F).

Inorganic Suspended Solids

At both sites, inorganic suspended solid (ISS) concentrations increased after rain events; however, the increase was more profound at the headwater site. The mean ISS concentration at the headwater site was 50 times higher following rain events than during fair weather conditions, while the mean organic suspended solid (OSS) concentration was only seven times higher following rain events. The majority of samples collected at the headwater site were 100 percent organic for most of the fair weather samples (Figure 8). At the tidal site, ISS concentrations were two times greater following rain events than during fair weather. This is consistent with the two-fold increase observed in TSS concentrations between fair weather and rain events. Post-rain ISS concentrations also were more variable than post-rain OSS concentrations at the tidal site (Figure 9).

Following rain events, ISS concentrations were higher than during fair weather conditions at both sites. ISS comprised 43 and 63 percent of TSS at the headwater and tidal sites, respectively. ISS concentrations ranged from below detectable levels to 26.3 ± 0.3 mg L^{-1} at the headwater site with a mean of 5.1 mg L^{-1} (Figure 10), which was 51 times higher than the fair weather mean. At the tidal site, ISS concentrations ranged from 1.3 ± 0.5 mg L^{-1} to 35.5 ± 0.5 mg L^{-1} with a mean of 13.7 mg L^{-1} (Figure 10). This value was approximately 2 times higher than the mean during fair weather. Ebb tide concentrations at the tidal site ranged from 3.9 ± 1.2 mg L^{-1} to 57.3 ± 1.2 mg L^{-1} with a mean of 14.8 mg L^{-1}. Low tide concentrations at this site ranged from 1.5 ± 1.0 mg L^{-1} to 47.3 ± 1.0 mg L^{-1} with a mean of 12.6 mg L^{-1}, and flood tide values ranged from 2.2 ± 0.8 mg L^{-1} to 38.6 ± 0.8 mg L^{-1} with a mean of 13.6 mg L^{-1}. Except for flood tide at the tidal site, ISS concentrations were significantly higher ($p<0.05$) following rain events than during fair weather (Table 3).

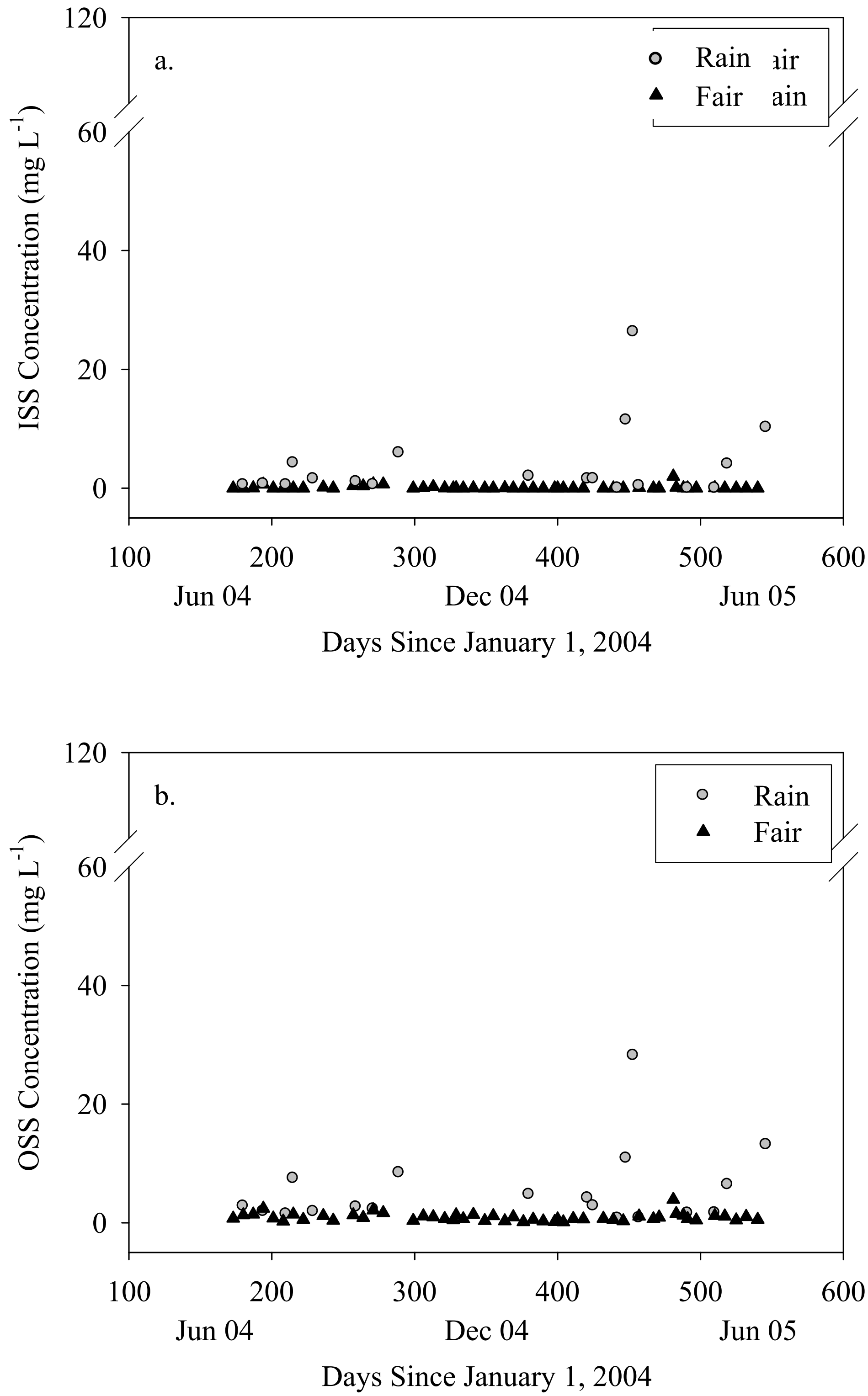


Figure 8. ISS concentrations (a) and OSS concentrations (b) at the headwater site during fair weather and following rain events. Concentrations shown are averaged over flood, low, and ebb tide.

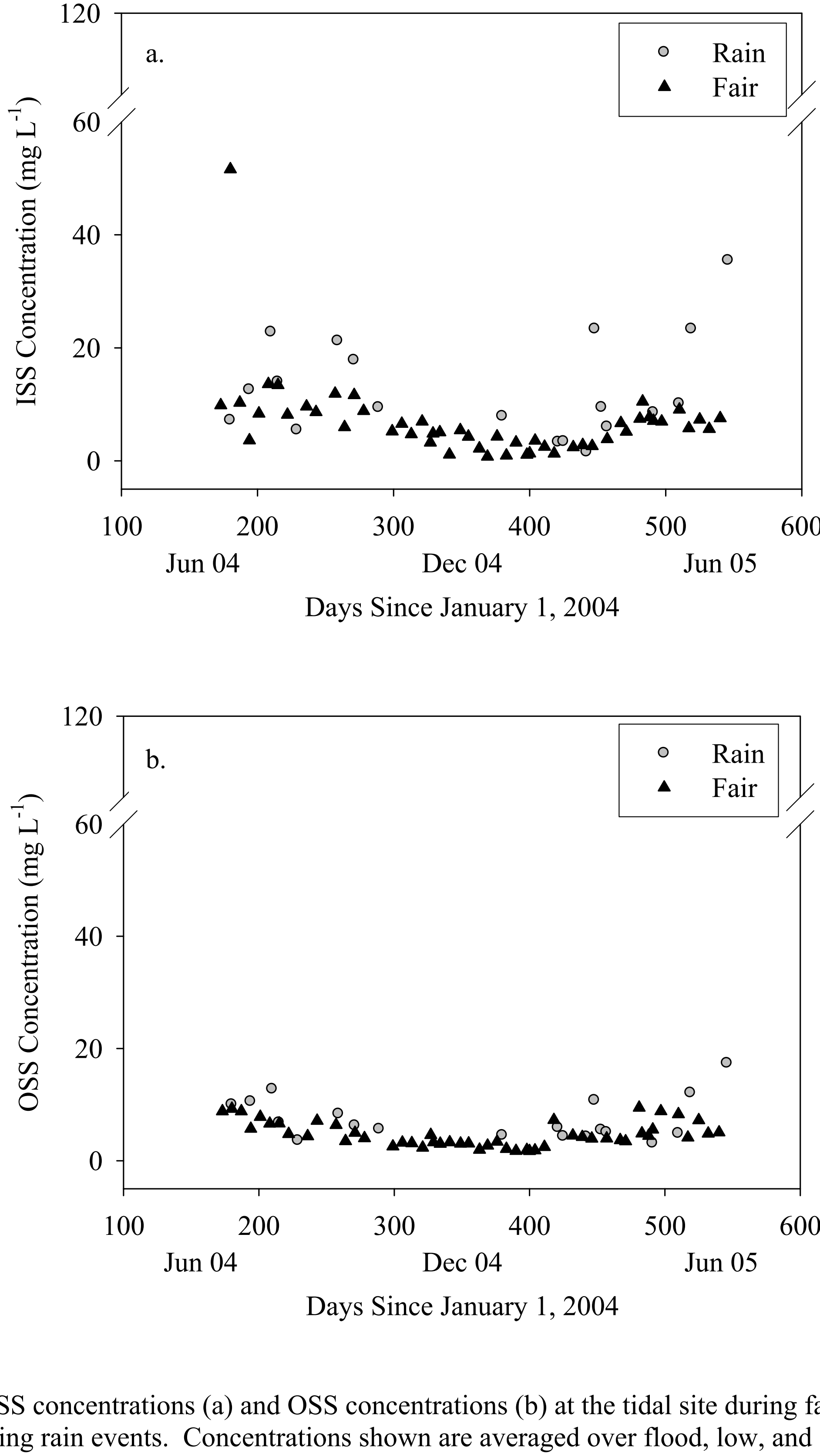


Figure 9. ISS concentrations (a) and OSS concentrations (b) at the tidal site during fair weather and following rain events. Concentrations shown are averaged over flood, low, and ebb tide.

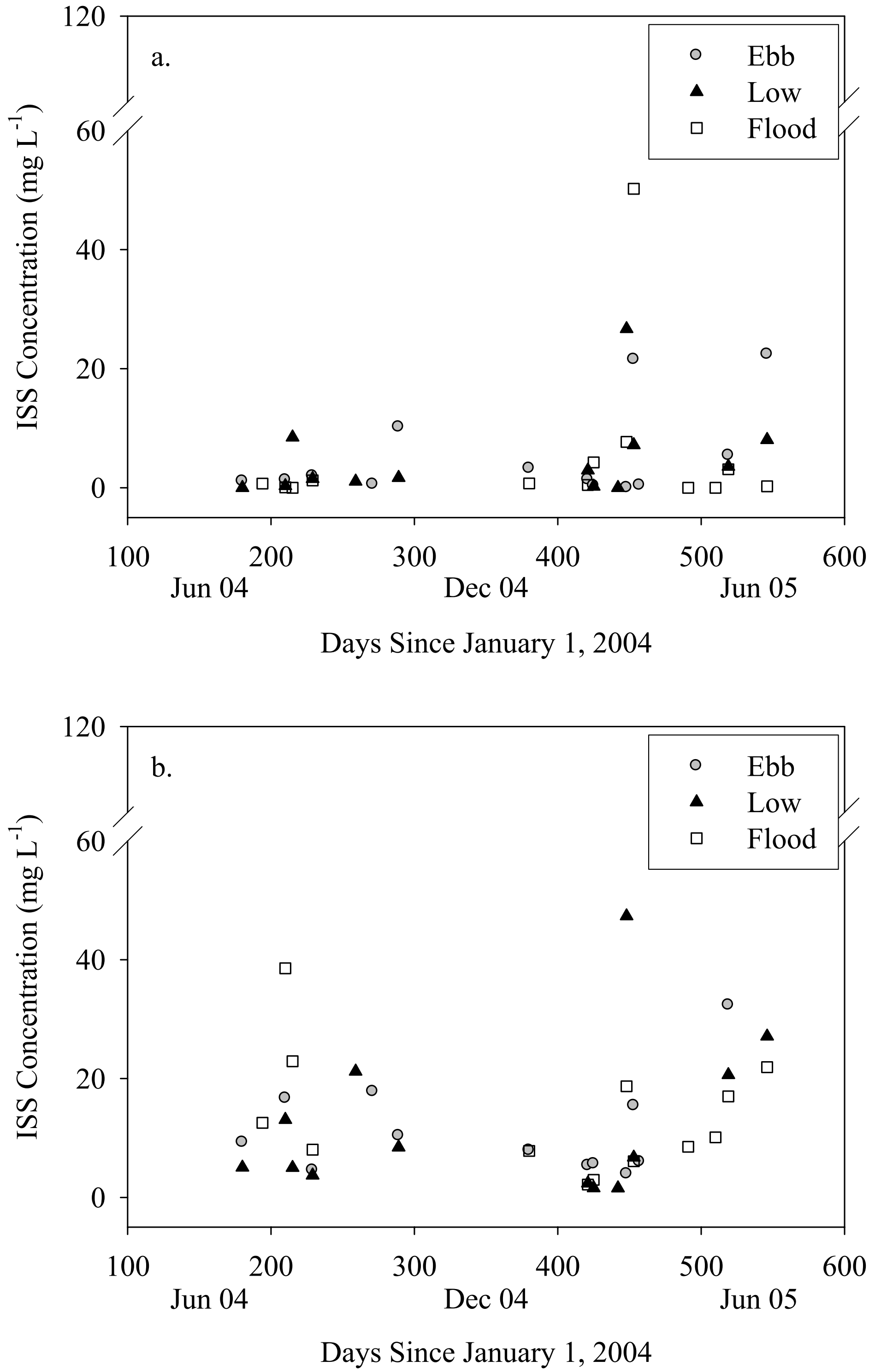


Figure 10. ISS concentrations at the (a) headwater site and (b) tidal site following rain events. Headwater values are broken down by tidal stage simply for comparison with the tidal site.

ISS concentrations were generally higher during the growing season, but not significantly different between seasons at either site. At the headwater site following rain events, the ISS fraction constituted 44 percent of TSS during the growing season and 34 percent of TSS during the non-growing season. When compared to fair weather ISS composition, it is evident that a greater increase in ISS concentrations occurred in the growing season than during the non-growing season at the headwater site. Specifically, ISS concentrations increased 30-times following rain events during the growing season, but only 24-times following rain events during the non-growing season. The mean ISS concentrations during rain events were 6.0 ± 0.5 mg L^{-1} and 2.4 ± 0.5 mg L^{-1} for the growing season and non-growing season, respectively. Following rain events, ISS concentrations were significantly higher at the headwater site for both the growing ($p=0.0045$) and non-growing ($p<0.0001$) seasons. At the tidal site, ISS constituted 64 percent and 60 percent of TSS for the growing season and non-growing seasons, respectively. Increases in percent inorganics between fair weather and post-rain conditions were slightly higher during the growing season than during the non-growing season at the tidal site. ISS concentrations at the tidal site were 17.2 ± 0.6 mg L^{-1} during the growing season and 9.0 ± 0.8 mg L^{-1} during the non-growing season. No significant difference in ISS concentrations existed between fair weather and rain events for either season at the tidal site (Table 4).

Spring tide concentrations at the tidal site ranged from 3.3 ± 1.5 mg L^{-1} to 21.2 ± 1.5 mg L^{-1} with means of 9.3 ± 2.5 mg L^{-1} at ebb tide, 9.1 ± 3.5 mg L^{-1} at low tide, and 6.8 ± 1.4 mg L^{-1} at flood tide. Of the sampled rain events, only one occurred during neap tide. For that event, neap tide concentrations measured 57.3 mg L^{-1} at ebb tide, 27.1 mg L^{-1} at low tide, and 21.9 mg L^{-1} at flood tide. No statistical analysis were conducted between post-rain spring tide and neap tide rain events due to the low occurrence of sampled neap tide rain events during the study period. No significant differences existed in spring tide ISS concentrations between rain events and fair weather conditions (Table 5).

Other Potential Factors

Influence of Marsh Inundation

Correlations between TSS and ISS concentrations and rainfall and rainfall intensity during periods of marsh exposure were examined in order to investigate the effectiveness of water as raindrop impact buffers. TSS and ISS concentrations and total rainfall during periods of marsh surface exposure were not significantly correlated (Table 6). TSS and ISS concentrations and rainfall intensity during periods of marsh surface exposure also were not significantly correlated (Table 6). Mean TSS concentrations following rain events that occurred during marsh exposure were 22.4 ± 1.7 mg L^{-1} at low tide and 21.6 ± 1.3 mg L^{-1} at flood tide. Following high tide rain events, times when the marsh was protected by water, mean TSS concentrations were 11.8 ± 0.7 mg L^{-1} during ebb tide and 22.6 ± 4.9 mg L^{-1} at low tide. One flood tide TSS concentration with a value of 15.0 mg L^{-1} was obtained following a high tide rain event. No significant differences existed between high tide and low tide rain events for either low tide and flood tide TSS concentrations. Mean ISS concentrations following rain events during marsh exposure were 12.6 ± 1.3 mg L^{-1} (56 percent of TSS) at low tide and 14.1 ± 1.0 mg L^{-1} (65 percent of TSS) at flood tide. Following high tide rain events, times when the marsh was protected by water, ISS concentrations were 7.2 ± 0.9 mg L^{-1} (61 percent) during ebb tide, 14.8 ± 4.5 mg L^{-1} (65 percent) at low tide, and 10.1 ± 0.0 mg L^{-1} (67 percent) during flood tide. ISS concentrations during periods of marsh surface exposure also were not significantly correlated to total rainfall or rainfall intensity (Table 6).

	Total Rainfall						Rainfall Intensity					
	TSS			ISS			TSS			ISS		
	R	p	n	R	p	n	R	p	n	R	p	n
Low	0.44	0.1758	11	0.40	0.2199	11	0.06	0.8701	11	0.04	0.8993	11
Flood	0.32	0.3092	12	0.27	0.3913	12	0.03	0.9158	12	0.03	0.9383	12

Table 6. R-values and p-values from correlation analysis between total rainfall and rainfall intensity during marsh exposure and TSS and ISS concentrations at low tide and flood tide.

Influence of Upland Inputs

Additional correlation analyses were conducted in order to investigate the relationship of post-rain TSS concentrations at the headwater site to post-rain TSS concentrations at the tidal site. These analyses included correlations between 1) ebb tide TSS concentrations at the headwater site and ebb tide TSS concentrations at the tidal site; 2) low tide TSS concentrations at the headwater site and low tide TSS concentrations at the tidal site; and 3) ebb tide TSS concentrations at the headwater site and low tide TSS concentrations at the tidal site. The same analyses were conducted for post-rain ISS concentrations. The last correlation was conducted to account for potential lags in the observed increase in concentration due to the time it might take for sediment input at the headwater site to be transported to the tidal site. No significant correlation however existed between TSS or ISS concentrations at the headwater site and tidal site following rain events.

Influence of Tidal Stage, Season, and Total Rainfall

A multi-way analysis of variance (MANOVA) was performed to determine the influence of tidal stage, season, and total rainfall on TSS and ISS concentrations at each site. Results show that at the headwater site a significant relationship existed between TSS concentrations and total rainfall ($p=0.0001$). No significant interaction existed between the other variables. At the tidal site, a significant relationship existed between TSS concentrations at both season and total rainfall ($p<0.0001$). A significant relationship also existed between the interaction of season and total rainfall and TSS concentrations ($p=0.0007$). Furthermore, results show that at the headwater site a significant relationship existed between ISS concentrations and total rainfall ($p<0.0001$). No significant interaction existed between the other variables. At the tidal site, a significant relationship existed between ISS concentrations for both season and total rainfall ($p<0.0001$ and 0.0003). A significant relationship also existed between the interaction of season and total rainfall and ISS concentrations ($p<0.0001$).

Correlation analyses were conducted to determine the relationship between mean monthly precipitation and mean monthly TSS and ISS concentrations at each site. Strong positive correlations existed between each site; however a significant relationship existed only for ISS concentrations at the headwater site (Table 7).

Marsh Surface Runoff

Runoff was collected from the marsh on eight days during which rain fell during low tide and the marsh surface was exposed; however, only four of the days produced quality data. One day qualified as a rain event (27.4 mm) as defined by this study and the other three did not (0.2 mm, 0.1 mm, and 0.3 mm). The rain event on November 12, 2004 had an intensity of 6.1 mm hr^{-1} during the collection period and produced 1.0 g m^{-2} of sediment (30 percent organic). For the other three events when runoff was successfully collected, intensities were less than or equal to 0.1 mm hr^{-1}. Less than 0.1 g m^{-2} of sediment (100 percent organic) was collected from runoff during two events with less than 0.1 mm hr^{-1} of rainfall (November 24, 2004 and February 21, 2005). For the event with an intensity of 0.1 mm hr^{-1} (May 5, 2005), 0.6 g m^{-2} of sediment (50 percent organic) was collected. No significant correlation existed between the amount of sediment collected and total rainfall or rain fall intensity (Table 8).

	TSS			ISS		
	R	p	n	R	p	n
Tidal	0.99	0.0919	12	0.98	0.1337	12
Headwater	0.96	0.1833	12	0.99	0.0162	12

Table 7. R-values and p-values from correlation analysis between mean monthly rainfall and mean monthly TSS and ISS concentrations.

	Total Rainfall				Intensity			
	Total	n	Inorganic	n	Total	n	Inorganic	n
R	0.82	4	0.88	4	0.82	4	0.89	4
p	0.1791	4	0.1158	4	0.1758	4	0.1131	4

Table 8. R-values and p-values for correlations between the total or inorganic fraction of sediment collected from marsh runoff and total rainfall or rainfall intensity during low tide rain events.

DISCUSSION

Bradley Creek serves as an important conduit of runoff and sediment between the upland and coastal environments. TSS concentrations are constantly changing in the tidal section of the creek due to varying water levels (Leonard et al. 1995, Angelidaki 1997, and Leonard 2003), precipitation (Leonard et al. 1995, Angelidaki 1997, and Leonard 2003), biological activity (Leonard et al. 1995) and upland inputs. Urbanization also has an impact on TSS concentrations in the creek (Mallin et al. 2000, Mallin et al. 2001, and Leonard 2003). In the headwater, non-tidal portion of the creek, TSS loads are influenced primarily by precipitation and urbanization practices (Leonard 2003). The objectives of this study were to 1) determine if TSS concentrations following rainfall events are greater than concentrations during non-rain periods, 2) determine the effect of upland runoff on TSS concentrations in the downstream tidal reaches, 3) determine if a seasonal fluctuation in TSS exists within the system due to changes in precipitation and stem density of marsh vegetation, 4) determine if significant differences in TSS concentrations exist between spring vs. neap tide rain events, and 5) determine if differences in TSS concentrations associated with rainfall events are dependent on the presence or absence of water on the marsh surface (i.e. high or low tide).

The results of this study indicate that TSS concentrations at both the non-tidal and tidal site increased following rain events. Extreme rain events did not produce significantly higher TSS concentrations than average rain events. This may be due to sediment exhaustion or the timing of the rain events. ISS concentrations also were higher following rain events except during flood tide at the tidal site. Seasonal fluctuations in TSS and ISS concentrations were evident at the tidal site only, even though precipitation was highest during the summer. Tidal stage (i.e. ebb versus flood) also influenced TSS and ISS concentrations, however, TSS and ISS were not significantly impacted by spring-neap variations. Overall, the results suggest that increases in ISS concentrations account for most of the observed variations in TSS concentrations.

Seasonal and Tidal Variations

During fair weather, TSS and ISS concentrations at the tidal site were higher during the growing season. Previous work has suggested that reworking of the marsh surface sediment by bioturbating organisms disaggregates the substrate to the point where it is more easily eroded and transported as runoff to adjacent creeks (Ward 1981; Hutchinson et al. 1995; Leonard et al. 1995). During this study, numerous fiddler crabs and burrows were observed especially in the summer and their activity may account for the increased TSS and ISS concentrations observed during the growing season. The organic fraction of TSS also increased, to a lesser degree, which may be due to the addition of detrital particles associated with enhanced biomass and/or increased phytoplankton in the creek water (Mallin et al. 2004) or increased benthic microalgae biomass on the marsh surface (Leonard et al. 1995). TSS and ISS concentrations showed no seasonal difference at the headwater site during fair weather. At the headwater site no bioturbators or evidence of burrows was observed. The organic fraction did increase during the growing season at the headwater site possibly due to the increase in vegetation along the channel banks and detrital material inputs. The abundance of above ground biomass, especially in the growing season, may also have affected TSS concentrations by buffering the impact of rain drops before they hit the soil surface. Following rain events, no seasonal differences in TSS and ISS concentrations existed at either site. It may be possible that raindrop impacts during the summer were subdued by denser vegetation on the marsh surface. Similar findings by

Settlemyre and Gardner (1975) reported that vegetation intercepts rainfall before hitting the ground surface, which lessens the impact of rainfall on sediment dispersion.

In general, flood tide TSS and ISS concentrations were higher than ebb tide and low tide TSS and ISS concentrations. This is characteristic of many systems that experience higher flood velocities than ebb velocities and is consistent with other research in Bradley Creek (Angelidaki 1997; Leonard 1997). This trend changed following rain events with ebb, low, and flood tide TSS and ISS concentrations being near equal, which may be the result of a small watershed or a reduction in sediment flushing (Mallin et al. 1998).

Although many researchers (e.g. Ward 1981; Leonard et al. 1995) have found spring tides to produce higher water levels, higher velocities, and higher TSS concentrations, those trends were not seen in this study. Tidal variations had no significant impact on TSS and ISS concentrations at the tidal site during fair weather. Spring tides did not produce significantly higher water levels than neap tides therefore it is presumed that tidal velocities also were not significantly higher. If tidal currents did not differ appreciably between spring and neap tides, there would be no physical mechanism available to significantly impact TSS concentrations over the fortnightly cycle.

Too few data were available to statistically examine spring/neap differences in TSS concentrations during rain events. Although several spring tide rain events were sampled, only one neap tide rain event was sampled within the study period. The neap tide rain event that was sampled (June 29, 2005) qualified as an extreme event and exhibited high precipitation totals and a high rainfall intensity. These data suggest that rainfall during neap tides, when water levels and velocities are lower, may result in elevated TSS, more neap tide rain events would need to be sampled to rigorously analyze the influence of rain during spring and neap tides.

Role of Rainfall

TSS and ISS concentrations were higher at both sites following rain events, which is consistent with the findings of other researchers (Ward 1981; Leonard et al. 1995; Leonard 2003; Voulgaris and Meyers 2004). At the headwater site, TSS concentrations were 12 times higher following rain events; however, at the tidal site, TSS concentrations were only 2 times higher following rain events. ISS concentrations at the headwater site increased over 50 times following rain events, but only doubled in magnitude at the tidal site. No significant difference existed between TSS concentrations at the headwater site and TSS concentrations at the tidal site following rain events.

Increased TSS and ISS concentrations at the headwater site can be explained by increases in the volume and velocity of runoff associated with urbanized watersheds. Increased runoff occurs in watersheds that have a high percentage of impervious surfaces due to urbanization (Arnold and Gibbons 1996; Holland 2004). Impervious surfaces prevent rainfall from infiltrating the soil and the lack of vegetation reduces surface roughness and increases runoff velocity (Hollis 1975; Schueler 1994; Arnold and Gibbons 1996; Veissman and Lewis 2003). For this study, channel water depths measured at the headwater site were significantly higher following rain events, showing evidence of a higher volume and velocity of water within the channel. This was observed several times during the study period including the sampled nor'easter in February 2005 (Figure 11). Elevated TSS and ISS concentrations were measured for this event, with a mean TSS concentration of 4.4 mg L^{-1} and a mean ISS concentration of 1.6 mg L^{-1}.

It is important to mention that sampling at the headwater site occurred downstream of the culverts. Culverts tend to store sediment and increased flow velocities may exist as water exits

Figure 11. Photographs of the headwater site following a rain event which caused increased TSS and ISS concentrations (February 28, 2005). The TSS concentration at the time the photo was taken was 9.2 mg L^{-1}. Elevated water levels and TSS are evident in these photographs looking (a) upstream and (b) downstream.

a culvert. In some systems, these trends may have a slight influence over TSS and ISS concentrations; however, in this system prior velocity measurements at each end of the culvert did not differ (Leonard personal communication, December 2, 2005).

Given the environmental setting of the tidal creek site, possible explanations for the observed increase in TSS include upland inputs (Mallin et al. 2000, Leonard 2003), marsh surface runoff (Mwamba and Torres 2002), and channel bank slumping and erosion (Schueler 1994, and Arnold and Gibbons 1996). The tidal site is directly surrounded by salt marsh however upland environments are sometimes within 5 m of the channel bank. In one instance, a plume of sediment passing through a broken silt fence from the uplands was observed entering the creek at the tidal site. Upland tributaries also may contribute a significant amount of sediment to the main reaches of the channel. With multiple tributaries flowing into the tidal site, it is possible that some portion of the increased sediment is being transported from these upland tributaries and into the tidal reaches. It is also possible that upland storm-water runoff is directly input to the tidal reaches throughout the watershed rather than flowing through the headwater channels first. Increases in ISS concentrations following rain events were not seen during either season at the tidal site. While bioturbation and plant growth is greater during the growing season, it is possible that bank stabilization by below-ground biomass and shielding by above-ground biomass (Settlemyre and Gardner 1975) prevented a significant increase in ISS concentrations following rain events at the tidal site. During the non-growing season, less biological activity may have resulted in greater sediment consolidation (or at least disaggregation) therefore making the dispersion and transport of sediment less efficient.

Rain-induced runoff from the marsh surface has been proposed as another explanation for increased TSS and ISS concentrations in tidal creeks following rain events (Settlemyre and

Gardner 1975; Mwamba and Torres 2002; Voulgaris and Meyers 2004). Even though post-rain TSS concentrations in the creek were higher than non-rain concentrations, the results of this study do not show a significant relationship between total rainfall or rainfall intensity and runoff from the marsh surface. It is possible, however, that the lack of significance is the result of too few data points. In addition, total rainfall occurring during low tide when the marsh surface was exposed was not significantly correlated to TSS and ISS concentrations. Similar regression analyses conducted by Hutchinson et al. (1995) also showed no significant relationship between rainfall during marsh exposure and suspended sediments.

Increased TSS and ISS concentrations at low tide and flood tide at the tidal site do not appear to be related directly to precipitation. If rainfall impact when the marsh surface was exposed had resulted in the disaggregation of surface sediment and its transport off the marsh surface, a significant relationship between rainfall and flood tide TSS concentrations should have been seen. The fact that a significant relationship was not observed even though post-rain TSS concentrations exceeded fair-weather TSS may indicate another potential source of material.

One such source may be channel bank slumping and erosion due to moving water or dispersion by rainfall on the unprotected interior channel walls (Settlemyre and Gardner 1975; Ward 1981; Schueler 1994). In general, bank stabilization by oyster beds and the roots of vegetation reduce the amount of erosion along channel banks. At the tidal site, however, few oyster beds were observed therefore it is presumed that the channel banks were stabilized only by vegetation. Following a nor'easter in February 2005, wrack deposits on uplands adjacent to the marsh suggest that higher water levels were present during the storm (Figure 12). This also may suggest that higher velocities were present during the event leading to a slight increase in TSS and ISS concentrations.

Figure 12. Photographs of wrack deposits on the (a) marsh and (b) adjacent land (February 28, 2005). Notice the wrack line on photograph (b) showing where the water line had reached during the storm.

Another explanation of increased TSS and ISS concentrations at the tidal site is the timing of rain events. Rain events occurring during ebb tide and low tide together produced higher TSS and ISS concentrations than rain events occurring at either tidal stage alone. This suggests that the turbulence created by rainfall prevented sediment from settling during the low tide lag, supporting the measured increase in TSS and ISS concentrations during low tide at the tidal site. It has also been found that sediment flushing rates decrease as a result of rainfall. Mallin et al. (1998) found that following rain events, flushing rates fell from 44 to 49 percent to only 30 percent per tidal cycle, suggesting that fresh water runoff favors the retention of suspended sediment in the tidal channel. However, these are not the only potential sources of increased sediment to the tidal site during or following rain events.

Potential Sources of Sediment to the Tidal Site

During fair weather, the main contributors of sediment are the tidal channel itself and the ICWW. Sediment within the creek is constantly being deposited and re-suspended by tidal variations. In Bradley Creek, flood tide flow velocities have been found to be greater than ebb tide flow velocities (Angelidaki 1997). In addition, a tidal asymmetry exists with ebb tide lasting longer than flood tide (Angelidaki 1997). In this study, TSS and ISS concentrations in the creek were generally highest during flood tide
and lowest during low tide, which is consistent with other studies in this flood-dominated system (Angelidaki 1997).

Runoff collected from the marsh surface during rain events produced samples with 30 to 100 percent organic material. Samples with 100 percent organic material, which were collected with minimal rainfall and low intensities, likely contained material from only the organic microlayer found on many marsh surfaces (Ribelin 1978, Seliskar and Gallaher 2005, Leonard personal communication September 17, 2005). It may also be possible that sediments washed from plant stems by the rain are being transported through the marsh towards the tidal creek channel as suggested by Stumpf (1983). This theory suggests that only a small amount of sediment, if any, is being transported from the marsh surface to the tidal creek channel. Other samples, collected under more intense rain events, show a greater amount of inorganic material. This data suggests high intensity rain events are required to break through the organic microlayer and disperse inorganic material on the marsh surface. Therefore, raindrop impacts during low intensity rain events may not have the potential to remove inorganic material from the marsh surface even if the total rainfall for the event is high.

Another source of sediment is the creek mouth at the ICWW. Sediment in the ICWW enters the tidal creek system during flood tide. If TSS concentrations in the ICWW increase, such as during a very wide spread runoff event or during periods of elevated wave activity, then TSS concentrations in the tidal creek may increase as well.

Following rain events, two other sources of sediment to the tidal creek channel become important: the marsh surface and upland inputs. As stated previously, organic material composed one-third to all of the runoff during low tide rain events. TSS data, however, do not support this (Table 9), and it seems that other sources are more significant contributors to TSS concentrations following rain events.

The sediment load at each site was estimated to determine the percent of the load at the tidal site that was accounted for by the concurrent load at the headwater site following rain events. Several factors were used to complete these estimations; they include flow velocities,

Total sediment collected (kg)	Inorganic material collected (%)	TSS (mg L^{-1})	Projected amount of sediment in channel (kg)	Amount of sediment to come from source other than marsh surface (kg / %)	Rainfall (mm)
130	0	10.4	624	494 / 79	0.2
122.5	4	12.2	732	610 / 83	0.1
1850	57	11.6	696	0	0.3

Table 9. Runoff calculations results based on total sediment collected from the marsh during low tide rain events and the flood tide TSS concentrations at the tidal site.

channel cross-sectional area, and percent of watershed runoff represented by the headwater site. The following calculation was used to estimate sediment loads for each site:

$$Q_s = (A*V)*C,$$

where Q_s is the sediment load in g sec^{-1}, A is the area in m^2, V is the velocity in m s^{-1}, and C is the TSS concentration in g m^{-3}. At the tidal site, the typical values for A and V were 7.5 m^2 and 0.25 m/s, respectively. At the headwater site, the typical values for A and V were 1 m^2 and 0.20 m/s, respectively. The percent of the sediment load at the headwater site that accounted for the concurrent load at the tidal site was significantly and positively correlated to rainfall ($R=0.58$, $p<0.05$).

Upland runoff estimations suggest that upland inputs to the tidal reaches are significant although they probably account for less than 100 percent of the increase in TSS at the tidal site. TSS concentrations throughout the watershed are exacerbated by construction activities. Construction activities were observed near both sites during the study period and during rainfall events, unprotected sediment from these areas may have been transported into various tributary channels of Bradley Creek. Once sediment is transported into channels, it can follow many pathways. Sediment can be deposited on the channel bed in the headwaters or transported to the tidal reaches of the creek. Depending upon the tidal stage, the transported sediment can be deposited on the marsh surface or in the tidal channel. Organic inputs from upstream are important to the marsh ecosystem because they provide food for many organisms, including snails, worms, and fiddler crabs, living in the marsh environment. Sediment not deposited on the marsh surface of in the tidal channel can be transported further downstream towards the Atlantic ICWW.

CONCLUSION

Sedimentation and other pollutants associated with sedimentation in Bradley Creek have many negative environmental and economic implications (Mallin et al. 2000; Mallin et al. 2001). Contaminated waters may cause fish kills and cause shellfish to become hazardous for human consumption. In addition, anthropogenic contaminants may cause waters to be too hazardous for human recreational purposes (Mallin et al. 2000; Mallin et al. 2001). Precipitation, water levels, TSS, and runoff data were collected over one year in the Bradley Creek watershed to test the relationship between TSS and rainfall. Major findings of this study are 1) TSS and ISS concentrations following rain events were greater than TSS and ISS concentrations during fair weather at both sites; 2) increases in TSS at the tidal site following rain events are impacted by upland runoff more so than marsh runoff, however a precise estimate of the amount of upland inputs to the tidal site could not be calculated with the data collected during this study; 3) TSS and ISS concentrations were higher during the summer than during the winter at the tidal site. The headwater site showed no significant change in TSS and ISS concentrations seasonally; 4) neap tide TSS concentrations were greater than spring tide concentrations following neap tide rain events; and 5) low tide rain events did not produce significantly higher TSS and ISS concentrations than did high tide rain events, therefore the presence of water on the marsh surface does not seem to be significant for this study.

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Appendix A. Mean TSS and ISS concentrations for each site and tidal stage during fair weather and rain events. P-values are shown for the comparison between fair weather and rain events for each site and tidal stage.

Site	Stage	Rain or Fair	n	Mean TSS (mg L^{-1})	p-value	Mean ISS (mg L^{-1})	p-value
Tidal	Ebb	R	13	22.5	0.0010	14.8	0.0014
		F	43	10.9		6.3	
	Low	R	13	21.8	<0.0001	12.6	<0.0001
		F	46	7.9		2.9	
	Flood	R	13	20.9	0.0318	13.6	0.0998
		F	45	13.5		9.2	
Headwater	Ebb	R	13	11.7	<0.0001	5.4	<0.0001
		F	43	1.2		0.2	
	Low	R	13	11.0	<0.0001	4.7	<0.0001
		F	46	0.9		0.1	
	Flood	R	13	13.1	0.0086	5.3	0.0127
		F	44	0.9		0.1	

Appendix B. Mean seasonal TSS and ISS concentrations for each site during fair weather and rain events. P-values are shown for the comparison between fair weather and rain events for each site and each season.

Site	Season	Rain or Fair	n	Mean TSS (mg L^{-1})	p-value	Mean ISS (mg L^{-1})	p-value
Tidal	Growing	R	15	26.8	0.0332	17.2	0.0610
		F	29	14.9		8.8	
	Non-Growing	R	4	15.1	0.0072	9.0	0.0885
		F	21	6.7		3.7	
Headwater	Growing	R	15	13.5	0.0028	6.0	0.0045
		F	29	1.3		0.2	
	Non-Growing	R	4	7.0	<0.0001	2.4	<0.0001
		F	21	0.8		0.1	

Appendix C. Mean spring tide TSS and ISS concentrations for the tidal site during fair weather and rain events. P-values are shown for the comparison between fair weather and rain events for each tidal stage.

Tidal Type	Tidal Stage	Rain or Fair	n	Mean TSS ($mg\ L^{-1}$)	p-value	Mean ISS ($mg\ L^{-1}$)	p-value
Spring	Ebb	R	3	14.0	0.6663	9.3	0.5548
		F	7	12.0		7.3	
	Low	R	3	15.3	0.2983	9.1	0.1633
		F	7	8.8		3.1	
	Flood	R	3	11.8	0.5452	6.8	0.4416
		F	6	16.1		10.5	
Neap	Ebb	F	10	8.6	N/A	5.0	N/A
	Low	F	12	5.3		2.2	
	Flood	F	12	9.0		5.8	